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# WETLANDS AND THEIR ROLE IN TREATING ACID MINE DRAINAGE
# A LITERATURE REVIEW

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ELLIOT LAKE LABORATORY

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# WETLANDS AND THEIR ROLE IN TREATING ACID MINE DRAINAGE
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## ABSTRACT

An updated literature review pertaining to construction, use and performance of wetlands in treating acid mine drainage (AMD) is presented. The scope of the review is limited to the use of wetlands in controlling acid generation and metal release from mining wastes.

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Key words: Wetlands; Acid mine drainage;

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## BACKGROUND

A joint research program entitled "Development of Wet Barriers on Pyritic Uranium Tailings" has been established between the Elliot Lake Laboratory, CANMET and Rio Algom Ltd. The objective of the program is to establish a saturated hydrologic condition at the surface of the tailings and to develop an appropriate wetland vegetative cover to:

1) act as an oxygen barrier and hence control acid generation;
2) stabilize the surface; and
3) minimize surface water contamination.

To date, above grade inactive tailings impoundments are successfully rehabilitated with conventional revegetative land reclamation technology where the tailings surface and dam slopes are stabilized with agronomical or native terrestrial vegetation consisting of a mixture of several grasses and legumes. This type of reclamation has been very effective in controlling erosion and improving aesthetics. However, the expected benefits of vegetation in reducing acid generation from reactive tailings containing sulphides have not been realized (Veldhuizen et al. 1987).

Wet barriers, such as water and or wetland cover on tailings, are believed to be more effective in preventing acid generation by cutting off the oxygen supply within tailings (Nicholson, 1989). The anoxic conditions so produced further support the growth of anaerobic heterotrophes such as sulphate reducers which, with the breakdown of sulphates, produce hydrogen sulphide, thereby precipitating dissolved metals as sulphides (Hedin, 1989 and Hedin et al. 1989).

## LITERATURE REVIEW

A literature search pertaining to the wetlands technology applicable to

this project was conducted using computer search facilities of the Library and Documentation Services Division (LDSD), CANMET, and Laurentian University, Sudbury. The keywords used were: wetland(s), bog(s), marsh(land), construction, management, restoration, wastewater, acid mine drainage (AMD), pollution, effluent, treatment, control, tailings and mine waste.

Constructed or artificial wetlands are being used increasingly in the U.S. for the treatment of acid mine drainage from coal wastes and slurry ponds, municipal wastewater, and for the management of water resources and wildlife. No published information on the specific use of wetlands as covers on tailings was retrieved.

The subject of wetlands has been previously reviewed by Chan et al. (1982), U.S. EPA (1984), Athanus (1986), Washington State Department of Ecology (1986), and Hiel (1986). A course on the construction of wetlands for the treatment of mine water was conducted by Kleinmann et al. (1986). Wheeland (1987) prepared notes and annotated lists of selected references regarding the role of wetlands in mine closure for the Reactive Tailings (RATS) Technical Working Group meeting. Other relevant information is available as: Conference proceedings: National Symposium on Wetlands (1979), American Water Resources Association; Wetlands and Water Management of Mined Lands, The Pennsylvania State University (1985) edited by R.P. Brookes et al.; Design Principles for Wetland Treatment Systems, Hammer et al. (1983); Wetlands and Coal Surface Mining: a management handbook, Cardamone et al. (1984); and Wetlands Ecological books: Wetlands, Mitsch and Gosselink (1986), Van Nostrand Reinhold Co.; and Wetlands Ecology, Productivity and Values: Emphasis on Pennsylvania, the Pennsylvania Academy of Sciences (in press (1989).

Wetlands research applicable to this project is briefly summarized below.

# WETLANDS

## DEFINITION

Wetlands is a very general term, encompassing swamps, marshes, bogs, wet meadows, fens, etc. Freshwater wetlands classified as 'palustrine wetlands' by U.S. Fish and Wildlife Service (Cowardine et al. 1979), are chiefly associated with river floodplains, upland depressions, margins of lakes and ponds, limestone sinkholes, groundwater seepage slopes, and other areas where the water table is at, or near, the surface during the growing season. In northern latitudes wetlands are also found in freeze and thaw basins, saturated permafrost areas and below melting snow beds.

Hydrologic forces maintain wetlands in many ways. Most palustrine wetlands are flooded at some time during the year from only a week or two early in the growing season to permanently flooded. Wetlands occurring on slopes may never be flooded, yet the soils remain saturated for all or most of the growing season by groundwater seepage. Differences in local hydrology and other factors affect the plant composition of individual wetlands (Tiner 1985).

## VEGETATION CLASSIFICATION

Palustrine wetlands are dominated by persistent vegetation, such as trees, shrubs, and herbaceous plants that remain visible in wetlands through the winter and into the following spring. Palustrine wetlands are represented by three major vegetation types (Tiner 1985):

### 1. EMERGENT WETLANDS

Palustrine emergent wetlands are dominated by erect, herbaceous vegetation, including many sedges and grasses. These wetlands are commonly referred to as marsh, wet meadows, fen, inland salt marsh and alkali marsh,

depending on individual characteristics. Many emergent wetlands are dominated by one or a few species. Common marsh plants include: cattails, bulrushes, rushes, sedges, wild rice, rice cutgrass, reed canary grass, blue-joint, burreeds, smartweeds, arrowheads, pickerelweed, and arow arum.

Emergents are rooted hydrophytes where most of the plant material is above the water surface. The water levels must fluctuate for proper growth and seeds will germinate if drawdown (lowering of water level to bottom substrate) occurs in late summer, early fall. They can also reproduce vegetatively by runners with the persistent species (cattail, sedges, and some rushes) remaining upright and robust after death and frost in the fall.

2. SCRUB-SHRUB WETLANDS

Freshwater wetlands, dominated by woody vegetation less than 6.1 m (20 ft) tall represent palustrine scrub-shrub wetlands. Although not as abundant as emergent and forested wetlands, they occur widely throughout. These wetlands are commonly called bogs, pocosin, scrub-carr or scrub swamp.

Northern and southern peat bogs are particularly interesting types of scrub-shrub wetlands. Both types are rarely flooded and are generally characterized by saturated organic soil with water at or near the surface for most of the year. In Alaska, these wetlands are underlain by permafrost. Northern bogs are prevalent in isolated depressions, along river courses, and along the margins of lakes. Typical northern bog plants include leather leaf, sweet gale, cotton grass, peat mosses (Sphagnum spp.), bog laurel, and sedges as well as stunted trees of black spruce, tamarack, lodgepole pine and balsam fir.

Southern bogs occur along the U.S. southeastern coastal plain and are locally called pocosins. They are found on broad flat plateaus usually apart from large streams. Pocosins are dominated by evergreen shrubs of pocosin

pine, alder-leaved pepperbush, low gallberry holly, fetterbush and titi. Other important scrub-shrub wetlands are characterized by buttonbush, alders, willows, dogwood, and saplings of trees like red maple, cottonwood and aspen.

Woody hydrophytes usually prefer seasonally flooded conditions (i.e., cannot tolerate year round saturation) and can be transplanted with care, but are slow to pioneer on newly formed wetlands. Examples include: willows, dogwoods, blueberries, spirea, and specialized acid bog species (e.g., leather leaf, rosemary).

Mosses, most commonly sphagnum and non-flowering primitive vascular hydrophytes, vary in their water level and water acidity requirements and most form dense mat-like beds. Shade tolerance also varies considerably for mosses (Kleinmann et al. 1986).

## 3. FORESTED WETLANDS

Forested wetlands are dominated by trees taller than 6.1 m (20 ft). In the eastern U.S. they are the most abundant wetlands type. They include such diverse types as black spruce bogs, cedar swamps, red maple swamps, and bottomland hardwood forests. As in other inland wetlands, flooding is extremely variable depending on regional climate, topographic position, and local hydrology. In the northern U.S. important trees of the wetter swamps are red maple, ash and tamarack. Drier swamps, those flooded only briefly during the growing season, are characterized by silver maple, pin oak and sycamore in the northern areas, and by sweet gum, loblolly pine, slash pine, tulip tree, American beech, sycamore, water hickory, pignut hickory, oaks (black oak, laurel oak, and willow oak) in the southern U.S.

For large woody hydrophytes that usually prefer temporary flooded conditions in spring or winter, soils must not be saturated year round except for specialized trees such as bald cypress. With care, young stems of elms,

black ash, red maple, and black spruce can be transplanted but the development to maturity is slow.

Shallow open water bodies such as pond and playa lakes less than 8 ha (20 acres) in size and less than 3 m (6.6 ft) deep also comprise palustrine wetlands. The primary vegetation classes are:

a) SUBMERGENT

Submergent hydrophytes require complete immersion, and are generally rooted in the bottom. They require stable water levels and most require relatively clear, unpolluted waters. Examples include pondweeds, wild celery, elodea, water milfoil and fanwort.

b) FLOATING

Floating hydrophytes are either free floating on the surface (duckweed) or are rooted in the bottom with major leaves floating at the surface. Water levels for this type of vegetation can vary somewhat but must be sufficiently deep during the growing season. Water quality can also vary and these plant types are more tolerant of moderate nutrient loads. Examples include spatterdock, watershield and water lilies. Water hyacinths are used for treatment of sewage effluent in the southern states.

## CHARACTERISTICS

For wetlands at least one of the following three characteristics must be present (Brooks in Kleinmann 1986):

1. PRESENCE OF HYDROPHYTES

Wetland vegetation (as classified above) which includes many different life forms all requiring specific habitat conditions.

## 2. PRESENCE OF HYDRIC SOILS

Soils specifically developed under saturated conditions at some time of the year. These can be mineral or organic types; mineral soils can vary from clay to sand in particle size, whereas organic soils are composed primarily of decayed plant material. These include poorly decomposed fibric soils (sphagnum or sedge peat) or well decomposed mucks (fine particle size). Usually both types of soils are present in varying proportions.

Saturated soils are seldom, if ever, exposed to air and have a characteristic anaerobic zone (no appreciable oxygen present) which often appears gray or black. These can harbour anaerobic bacteria: sulphur reducing, iron oxidizing and manganese oxidizing species. These bacteria can exist on sediments, decaying plant material or other colonization surfaces.

Seasonally or temporarily flooded soils exhibit a mottling structure when viewed in a cut-away section. The saturated portions are often gray or black and these alternate with brown or yellow sections that are exposed to air/oxygen pockets. Exposed mud flats are also included in this classification.

## 3. PRESENCE OF WATER

Water is the driving force for the formation of any wetland. It controls the development of hydric soils and also controls the type of hydrophytes that are present. These in turn help to define the type of wetland that is present. In all wetlands, the land is saturated or flooded at some time of the year. It can vary from saturated bottom ponds and streams that are never exposed to air to temporarily saturated flood plains.

Water regime describes the hydrologic characteristic of a wetland, including flow (rapid currents vs. stagnant), depth and hydrologic connections, i.e., the water source.

Water quality: constituents and characteristics other than those of water itself affect the condition of a wetland and its ability to survive and function. These may include sediments that affect turbidity, nutrients (e.g., nitrogen, phosphorus, etc.) that affect productivity, trace elements (e.g., iron, sulphur, etc.), dissolved gases (e.g., oxygen, carbon dioxide, hydrogen sulphide, etc.), pollutants (any material that is found in excess or toxic quantities), or temperature which is affected by incoming water sources and the amount of solar radiation received.

## VALUES

Whether natural or artificial, wetlands have many ecological and socio-economic functions and values. The old notion of viewing wetlands as wastelands is rapidly declining due to a better understanding of wetland function and to a more informed public (Tiner 1984, and Greeson et al. (1979). The natural benefits of wetlands can be divided into three basic categories:

1. FISH AND WILDLIFE VALUES

   a) Fish and shellfish habitat;

   b) Waterfowl and other bird habitat;

   c) Fur bearer and other wildlife habitat;

   d) Endangered plant and animal habitat.

2. ENVIRONMENTAL QUALITY VALUES

   a) Water quality maintenance (pollution filter, sediment removal, oxygen production, nutrient recycling, and chemical and nutrient absorption);

   b) Aquatic productivity;

   c) Microclimatic regulator;

   d) World climate (ozone layer maintenance).

3. SOCIO-ECONOMIC VALUES

a) Flood control;

b) Wave damage protection;

c) Erosion control;

d) Groundwater recharge and water supply;

e) Timber and other natural products (peat, cedar, cranberries and blueberries);

f) Livestock grazing;

g) Fishing and shell-fishing;

h) Recreation;

i) Aesthetics;

j) Educational and scientific research.

## ACID MINE WATER TREATMENT

The idea of wetland treatment of acid mine water did not evolve from wastewater treatment. It developed, instead, out of observations of abandoned mines where acidic waters (acid mine drainage, AMD) were flowing into natural sphagnum (peatmoss) bogs, where instead of being adversely affected, the wetland appeared to cause an amelioration of the polluted water. At the Powelson Wildlife Area in Ohio, Huntsman et al. (1978) observed that dissolved acidity, iron, manganese and sulphate concentrations decreased as AMD flowed through a sphagnum bog. In a similar but more detailed study of an AMD input to Tub Run Bog, a sphagnum bog in West Virginia, Wieder and Lang (1982) observed that 50 m downstream of an AMD input, the pH of the interstitial water rose from less than 3.5 to greater than 5.0, sulphate concentrations dropped from 250 mg/L to 10 mg/L, and iron concentrations dropped from 50 mg/L to less than 2 mg/L. Sphagnum peat samples collected in Tub Run Bog had much higher iron concentrations than samples collected in a local unimpacted bog.

A limestone outcrop within the sampling area appears to have contributed to the change in pH.

Other studies that followed found, in fact, that acid drainage flowing through two wetland types (cattail marshes and peatmoss bogs) had qualities equal to and sometimes superior to those of nearby streams unaffected by mine drainage (Kleinmann et al. 1983, Tarleton et al. 1984, Burris et al. 1984, Gerber et al. 1985, Sencindiver and Bhumbla 1988, Samuel et al. 1988, Snyder and Aharrah 1984, etc.).

The researchers noted that these wetlands were dominated by plants that actually prefer acidic water, at least one type of moss typically fails if the pH is above 4 (Kleinmann et al. 1986). These plants also tolerate levels of sulphate and various metals that would eliminate most plant forms. Most important, these plants form the framework for a self-maintaining ecosystem that removes metals, mineral acidity and sulphates - precisely the parameters that differentiate acid mine drainage from rain water.

The understanding today is that wetland plants remove metals from acid water by three types of action: by adsorption (especially ion exchange): by consumption (plant uptake); and by simple filtration. Different plant species vary in their primary metal removal mechanism and relative efficiency. For example, the sphagnum species have high surface area and are extremely effective as ion exchange media. In addition, sphagnum is also a good filter for ferric hydroxide particulates. In contrast, Typha (cattails) do not have a lot of surface area but do accumulate iron and manganese, as much as 300 ppm Fe and 200 ppm Mn in the rhizome tissue, 45 ppm Fe and 52 ppm Mn in leaves (Snyder and Aharrah 1984). Analysis of algae from a wetland that was removing manganese from mine water demonstrated phenomenal plant uptake- Mn concentrations as high as 56,000 ppm (dry weight) were recorded.

Iron and manganese oxidizing bacteria are also very active in these

acidic wetlands; so much so that some researchers believe they are the most critical aspect of metal removal in cattail marshes (Singer and Stumm 1970, Kleinmann and Crerar 1979, Nealson 1983, and Stone 1984).

In the organic-rich substrate, other bacteria are active. Desulfovibrio desulfuricans, for example, convert the sulphate component of mine water to hydrogen sulphide. This in turn reacts with dissolved metals, adsorbed metals and precipitated metals to form insoluble metal sulphides. This is the eventual fate of all the metals removed from the acid water, as dead vegetation sinks to be replaced by new, but is also important as a primary removal mechanism. Absorption by the organic substrate (especially peat) can also be very high (Kleinmann et al. 1986, Hedin et al. 1989).

Finally, there are geochemical removal mechanisms occurring in the wetland which may be significant. For example, the cattail marshes that are most successful in removing manganese all have an incorporated layer of limestone beneath the organic substrate. This produces an environment of near neutral pH and high carbon dioxide concentrations (due to neutralization reactions) and may result in the precipitation of manganese carbonate.

Thus, from top to bottom, these acidic wetlands appear to offer a multitude of mechanisms for metal removal. According to Kleinmann (Chironis 1987), "the plants are helping remove the metals, the algae and the bacteria are helping remove the metals, everything we look at is helping us - it's just incredible. Part of our difficulty in optimizing such a system is that normally you minimize what is doing badly and enhance what is doing well, but here, everything is doing so well, so the question is which is doing the best for us".

## CONSTRUCTION

Wetlands are living biological systems with limited capacities,

therefore they can be damaged if these limits are exceeded. Excess nutrients, trace elements and sediments can act as pollutants. Insufficient quantities of water, nutrients or dissolved gases can also cause irreparable damage.

Successful design and construction of wetlands depends on defining the specific objectives and reasons for creating and/or restoring a particular type of wetland and on careful planning and implementation of these objectives within the biological limitations of a given wetland type and the design limitations for a given site.

Artificial wetlands, designed and constructed for specific usage have different design parameters which vary according to the requirements. Wetlands constructed for the treatment of wastewater or AMD have different design considerations than those for the control of flood, storm, and erosion or for wildlife habitat management. In this report, design considerations pertaining to AMD only are discussed. For other systems, the reader is referred elsewhere in the literature (Hammer and Kadlec 1983).

Wetlands designed specifically for treatment of AMD must be integrated into an overall hydrologic plan, both on and off the mine site. Not all the wetlands can meet all needs, and in many cases the needs will not be compatible. However, whenever possible, multiple functions and values of wetlands should be considered and incorporated into construction designs.

Wetlands have specific parameters that can be manipulated to facilitate the formation of the desired hydrologic regime, and hence, the desired ecological community. These characteristics are:

1. BASIN/CHANNEL MORPHOMETRY

These are physical characteristics of the wetland that can be manipulated, usually by using standard earth moving techniques and equipment. They include: a) size, b) shape, c) slope, and d) depth. The basin and

channel dimensions, its geometric shape, slope, and depth determine the treatment capacity of the area and establishment of the plant communities.

2. VEGETATIVE LIFE-FORM AND ARRANGEMENT

The life-form (i.e., physical structure, not necessarily the species), vegetation density, and interspersion (i.e., mixing of vegetation types and open water) will affect the efficiency of the system.

3. HYDROLOGIC REGIME

The permanence, periodicity, water velocity, microtopography, water source, and juxtaposition to other wetlands and terrestrial habitats all affect wetlands, and particularly the vegetation. The control of water regime and its quality have to be implemented to allow development of the wetland community before it can be effective.

The technique involves building a series of relatively shallow ponds, starting with an existing shallow lowland or an old sediment pond and filling it partially - or making shallow excavations about a meter deep. Some substrate and organic compost material is laid on the bottom to simulate a natural wetland and help root the plants. Composted organic substrate is better than merely using hay. If the incoming water is very acidic, it is also desirable to lay down some limestone on the bottom of the pond.

In terms of water depth, 8 to 10 cm of water above the substrate is best. Above this depth, the system begins losing its treatment efficiency. To maintain such a depth, the water should be permitted to overflow into channels that lead it through a series of excavations that form the wetland-pond system (Chironis 1987).

The U.S. Bureau of Mines, in cooperation with Dr. R. Brooks of the Pennsylvania State University, Dr. B. Huntsman of Wright State University, and Mr. B. Pesavento of Environment Analytic, Inc., as well as Dr. R. Kleinmann

(Kleinmann 1986), have provided the following information on constructing wetlands for treating acid mine water.

FLOW CAPACITY

A separate pond or wetland section should be built for each 20 to 40 L/min flow. Units for larger flows have shown flow-pattern problems and require more critical design criteria.

pH GOAL

The pH coming out of the seep should be above pH 4.0, although successful wetlands have been constructed that discharge at pH's as low as 3. Lower pH values mean that the substrate and humic strata should be improved and that the addition of limestone may be necessary.

MINERALS REMOVAL

Try for an iron loading (iron removal) of 50 parts per million or less. Higher loadings require size modifications and design parameters to prevent iron precipitate causing a die-out of the plants. Also try for a manganese loading of 10 to 15 parts per million or less. Over 20 parts per million requires two-stage designs.

DESIGN CRITERIA

The pond should be at least 5 sq m in area per flowing liter (200 sq ft per gallon U.S., with the flow parameter at maximum flow). The area should be protected from flooding and high speed run-off that could cause scouring. The excavation should be made with the concept that the wetland will be a permanent installation and self-sustaining.

During construction keep the work area as dry as possible, provide at least 0.5 m freeboard above the original planting, and provide a polishing and treatment area after the wetland to comply with discharge guidelines while the

wetland is developing.

PLANT MATERIALS

The easiest wetland flora to transplant is cattails. The broad-leaf version takes more abuse than the long, slender-leaf variety. Sphagnum moss and other mosses may be used but they are not very easy to obtain or transplant and may not survive if the water level is too high or too low.

Try to match the plant material to the conditions. Do not use plants from an area of a pH range 6.5 to 7.0, and then move them to an area with pH 3.9 to 4.2 The plants will be put under considerable stress and may not survive.

The cattails should have at least 300 sq cm of surrounding material around the base of stems. Dig the cattails out - do not pull them out, as this will often strip all the budding shoots during pulling.

GROWING MEDIA (SUBSTRATE)

The quickest way to obtain a high humic strata for lining the bottom is to use composted material such as the spent mushroom compost or compost made from woodlands debris during clearing.

A substrate high in calcium may be needed when there is a low pH, or a low pH and a manganese problem. Also, if sphagnum is used, try to grow the sphagnum by using baled peat moss for the substrate (but without limestone).

PLANT SETTING

When planting cattails, put the plants in the ground the way that they were growing before their removal. The roots should be covered and in the humic strata. The stems should be upright in the air.

The plants should be spaced on at least 0.6 m centres and staggered so there are no straight water channels. The plants are there to stabilize the

wetland and to spread and diffuse the flow.

When planting mosses, set them in conditions very near that from which the mosses originated. For best results the clumps should be planted in 20 x 20 cm squares in a checkerboard pattern. Mosses need to be wet but not flooded.

NUTRIENTS

If properly prepared, the bed will not require much fertilizing unless the algae and phyto-plankton fail to bloom. The wetland plants do not need much nitrogen and they already have enough calcium. A little phosphorus and potassium is all they may require.

WATER LEVEL

The water level in the wetland should be 5 to 10 cm deep. Should the level exceed 15 cm removing manganese will be difficult and there may be a freeze-over in the winter which will render the wetland ineffective for treatment.

The other problem with too much water is that it can drown the plants and also create an insect breeding ground.

FLOW CONTROL

The water should not become stagnant. If it does, a rather messy, smelly system may result. The flow velocity should be between 3 to 10 cm per second on the surface. The substrate flow should be very slow.

The velocity should not cause channelling. If channelling does occur, the channels should be blocked and the water dispersed with cross-dikes. If there is too much of a pitch in the wetland, the water will also channel.

For discharge control, the influent and effluent controls must be open channels and not pipes. Pipes invariably become filled with silt, dead

vegetation and of animal habitations. The result would be an unwanted rise in water level, flooding the area and washing it out.

Von Michaelis (1986) proposed a systems approach in developing an integrated biological system with enhanced effluent treatment capacity through engineering its ecology. The system employs more than one biological process simultaneously or in sequence to treat or polish the effluent. The integrated biological processes include plants, algae, fungi, bacteria, biomass and enzymes, etc.

## PERFORMANCE EVALUATION

The performance of constructed wetlands is measured in terms of their overall design objectives and survival potential. For AMD treatment, it is their functional ability in providing water quality goals as the system cycles through time and climatic conditions. These include changes in: temperature, precipitation, flow rate, water level, water chemistry, metals and sediment loadings, nutrient and trace metal concentrations, and micro-organisms. The U.S. Bureau of Mines has recently surveyed the performance of constructed wetlands in an attempt to identify the characteristics of successfully working systems (Hedin 1989, Grits et al. 1986, and 1987). Some of their findings are as follows:

Wetlands that are being constructed today are, generally, better designed. Plant establishment is more uniform since Typha (cattails) and a thick organic substrate became standard. Some of these sites are resulting in much better short-term water treatment than was considered possible five years ago. However, because none of these systems are more than several years old, no long-term data exists.

Despite promising laboratory and experimental results (Kleinmann et al. 1983, Tarleton et al. 1984, Burris et al. 1985, and Gerber et al. 1985),

virtually all field tests of Sphagnum-dominated constructed wetlands failed to provide sufficient water treatment for more than several months. Sphagnum proved quite sensitive to the stresses associated with transplanting, abrupt changes in water chemistry, excessive or insufficient water depth, and excessive accumulation of iron. At most sites the moss died within the first growing season (Hedin 1989).

Today, almost all wetlands constructed to treat AMD are planted with and dominated by Typha latifolia, common cattails. Typha is readily available to most sites, transplants well and has proven to be tolerant to wide ranges of water conditions (Sencindiver and Bhumbla 1988, Samuel et al. 1988, Snyder and Aharrah 1984). Occasionally, Scirpus spp. (bulrushes) and Equisetum spp. (horsetails) are also planted, but even these systems are generally dominated by cattails during the first several years of wetland operation.

The U.S. Bureau of Mines survey revealed that very few constructed wetland systems were improving the drainage chemistry enough to meet regulatory water quality standards. To date, the systems have been most successful in lowering iron concentrations, but rarely affect manganese (Hedin 1989). Wetlands constructed recently for treating higher volumes of more contaminated water are built with limestone base, mushroom compost for organic substrate and planted with Typha. Over the first eight months of operation of such a site, the outflow water contained, on average, 95% lower iron, 85% lower acidity, and 50% lower manganese than inflow water. Another system receiving a much larger load of acidity and metals with inflow rates of 40-80 L/min, pH less than 3.0 and iron concentrations averaging 280 mg/L, performed well during the first four months of operation (summer and early fall), where the system increased pH by several units, lowered acidity by more than 1300 mg/L and lowered iron concentration to dischargeable limits. During the winter the performance of the system decreased markedly, but the system still

lowered acidity by 1000 mg/L and iron by 200 mg/L. The wetland has not consistently affected manganese concentration.

The long term performance evaluation of wetlands is complicated by the preponderance of short term data and the very high performance during their first year of operation. Wieder et al. (1987) have argued that the high performance of new wetlands is partly due to adsorption and chelation abilities of the organic substrate, and that in most cases these capabilities are exhausted within several months. A second cause of high performance by newly constructed wetland is partial dissolution of limestone, which raises pH above 6.0 and greatly accelerates rates of abiotic iron oxidation and hydrolysis. In many wetlands that receive acid water, the limestone's effect decreases somewhat within several months, causing the site to acidify.

Despite the existence of acidic conditions, many wetlands remove substantial amounts of iron longer than is expected from adsorption and chelation processes. According to Hedin (1989), this removal is probably due to activity by iron oxidizing bacteria. Because the bacteria use reduced iron as an energy source, they are not subject to bioaccumulation or metal toxicity constraints. Given essential nutrients, oxygen, flow rate and sites for colonization and growth, the populations of iron oxidizing bacteria should grow to a size crudely in balance with the inflow ferrous iron concentrations. Iron-oxidizing bacteria are generally able to meet their nutritional needs in AMD and are capable of oxidizing iron at very low oxygen levels (Stone 1984), suggesting that flow rate and the number of suitable growth sites might be important determinants of activity.

A second potential source of long term effectiveness by these systems is the activity of dissimilatory sulphate and iron reducing bacteria. By stimulating the formation of iron sulphides, the contaminants in mine drainage revert back to their original form, pyrite. The bacteria require a source of

organic matter which in the short term is supplied by the organic substrate, but in the long term, must be supplied by the primary productivity of the wetland. The use of organic matter is potentially the most efficient iron removal mechanism. For every 48 g of carbon that is oxidized by the sulphate reducing bacteria, 56 g of iron is precipitated as pyrite.

Currently, most constructed wetlands only remove a small fraction of the inflow sulphate and iron by reducing processes, probably because most water flow is on top of the organic substrate. Natural systems are known where 75% of the net primary production cycles through sulphate reducing processes (Howarth et al. 1983), and where 50% of the iron sulphides found are retained in the sediments (Herlihy et al. 1987). Design changes that increase flow through the organic substrate to attain these levels of sulphate reduction could significantly increase system performance. This design strategy requires that the oxidation of anoxic environments be absolutely prevented, as this would cause destruction of iron sulphides and resolubilization of iron and production of sulphuric acid.

In the absence of any maintenance efforts, the long term metal removal capabilities of the system would likely be related to the primary productivity of the sites since organic matter is an important component of heterotrophic metal oxidation, bacterial reduction activity, adsorption and chelation processes. For low flow, low concentration situations, the productivity of a small constructed wetland might provide a long term treatment solution. However, when iron concentrations rise above 25 mg/L, the area of wetland needed to remove iron increases by 1-2 orders of magnitude.

For those situations where flow and contamination is such that an abandoned wetland cannot be expected to provide long term performance, long term maintenance efforts will be necessary. Periodic spreading of crushed limestone or lime in the system raises pH, increases plant growth, and metal

removal. Fertilization of wetlands could substantially increase productivity and the importance of carbon related processes. Where plant growth cannot provide sufficient organic matter, compost might be periodically added. For systems which treat high loads of metals, periodic removal of metal-laden substrate (and destruction/rebuilding of the wetland) might be necessary.

Short term data developed to date for many constructed wetlands precludes their total abandonment. The long term performance characteristics, maintenance needs, and costs associated with current constructed wetland designs are not yet established. In the U.S., the Office of Surface Mining, Reclamation and Enforcement, which oversees state agency enforcement of water quality standards at mining sites, does not at present, view constructed wetlands as viable water treatment systems unless they are backed up with chemical systems.

In Canada, M. Silver of Marvin Silver Scientific Ltd. designed and constructed a wetland system in 1988 to treat effluent from a pyritic slate quarry in Halifax, Nova Scotia. Though the data were short term, they showed increase in pH from 3.0 to 6.0 and concentrations of all dissolved metals decreased: aluminum by 97%, arsenic by 93%, cobalt by 86%, iron by 83%, nickel by 59%, and zinc by 61%. Copper, lead and manganese concentrations did not decrease but the decrease in the sulphate concentration by 77% indicated the presence and effectiveness of the biological removal of this anion (Silver 1989).

Griffiths (1988), and Kalin and Van Everdinger (1987) tried experimental field test plots containing various saturated wet covers and wetland vegetation on high sulphide base metal tailings and evaluated their suitability in preventing acid generation. The authors also investigated various methods of establishment and propogation of wetland vegetation on tailings and observed that:

1. Terrestrial moss cover curtailed precipitation infiltration on dry surface areas whereas the vascular plant covers had no amelioration effect on the underlaying tailings; and
2. Wetlands established in waterlogged, submerged sections and seepage areas reduced water infiltration, acid generation and removed metals; hand transplanted cattails showed a 200% population density increase after one year; hydroponic methods tested to date indicated little promise; seed germination of some wetlands plants was also reported on neutralized pyrrhotite tailings; and iron removal in seepages was catalyzed by the organic matter strata surface.

Preliminary data observed by Griffiths (1988) showed that a wet organic layer over pyrrhotite tailings resulted in lower concentrations of sulphate, iron, copper, nickel and increased pH compared to leachates from dry tailings, and upon drying out, all metal concentrations increased and pH decreased, with the rate depending upon the ability of the cover material to retain moisture.

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